

VSBL Electron Neutrino Disappearance

Carlo Giunti^(a), Marco Laveder^(b)

(a) *INFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy*

(b) *Dipartimento di Fisica “G. Galilei”, Università di Padova, and
INFN, Sezione di Padova, Via F. Marzolo 8, I-35131 Padova, Italy*

Abstract

We consider possible indications of Very-Short-BaseLine (VSBL) electron neutrino disappearance into sterile neutrinos in MiniBooNE neutrino data and Gallium radioactive source experiments. We discuss the compatibility of such a disappearance with reactor and MiniBooNE antineutrino data. We find a tension between neutrino and antineutrino data which could be due to: 1) statistical fluctuations; 2) underestimate of systematic uncertainties; 3) exclusion of our hypothesis of VSBL ν_e disappearance; 4) a violation of CPT symmetry. Considering the first possibility, we present the results of a combined fit of all data, which indicate that $P_{\nu_e \rightarrow \nu_e} < 1$ with 97.04% CL. We consider also the possibility of CPT violation, which leads to the best-fit value $A_{ee}^{\text{CPT,bf}} = -0.17$ for the asymmetry of the ν_e and $\bar{\nu}_e$ survival probabilities and $A_{ee}^{\text{CPT}} < 0$ at 99.7% CL.

1 Introduction

The MiniBooNE collaboration confirmed recently [1] the initial results on the search for short-baseline $\nu_\mu \rightarrow \nu_e$ oscillations reported in Ref. [2]. The new analysis confirms the absence of a signal in the 475 – 3000 MeV energy range due to $\nu_\mu \rightarrow \nu_e$ oscillations with a Δm^2 compatible with the indication of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations found in the LSND experiment [3]. It confirms also the anomalous excess of low-energy ν_e -like events reported in Ref. [2]. The MiniBooNE collaboration have also presented recently the first results for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel [4, 5], which however are not as precise as the neutrino data because of a much lower statistics. Again, there is no evidence for a signal in the 475 – 3000 MeV energy range due to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations compatible with the indication found in the LSND experiment. More interesting, there is also no evidence of a low-energy anomalous excess of events.

In Ref. [6] we proposed an explanation¹ of the MiniBooNE low-energy anomaly through the Very-Short-BaseLine (VSBL) disappearance of ν_e 's due to oscillations into sterile neutrinos generated by a large Δm^2 in the range

$$20 \text{ eV}^2 \lesssim \Delta m^2 \lesssim 330 \text{ eV}^2, \quad (1)$$

which is motivated [6, 11, 12] by the anomalous ratio of measured and predicted ^{71}Ge production rates,

$$R_{\text{Ga}} = 0.87 \pm 0.05 \quad [13], \quad (2)$$

observed in the Gallium radioactive source experiments GALLEX [14, 15] and SAGE [13, 16–18]. As shown in Ref. [6], the range of Δm^2 in Eq. (1) is compatible with the upper bounds on neutrino masses obtained in tritium β -decay and neutrinoless double- β decay experiments.

The large Δm^2 in Eq. (1) implies an oscillation length of MiniBooNE neutrinos and antineutrinos which is shorter than the source-detector distance of about 541 m:

$$L_{\text{osc}}^{\text{MB}} = \frac{4\pi E}{\Delta m^2} \lesssim 400 \text{ m}, \quad (3)$$

where $E < 3 \text{ GeV}$ is the neutrino energy. Therefore, the disappearance probability of electron neutrinos and antineutrinos averaged in each energy bin is approximately constant² over the MiniBooNE energy spectrum (CPT implies that $P_{\nu_e \rightarrow \nu_e} = P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$; see Ref. [21]).

At first sight, explaining the anomalous MiniBooNE low-energy excess of ν_e -like events with ν_e disappearance seems a contradiction. Indeed, we must introduce another ingredient, a factor f_ν which takes into account the uncertainty of the normalization of the background prediction, which receives a substantial contribution from the uncertainty of the normalization of the calculated neutrino flux (see Ref. [22]). The background events in the MiniBooNE data analysis are divided in ν_e -induced events and misidentified ν_μ -induced events. The ν_e -induced events are produced by the ν_e 's in the beam generated at

¹ Other explanations have been proposed in Refs. [7–10].

² The analysis of MiniBooNE data with an energy-dependent ν_e disappearance probability due to a $\Delta m^2 \lesssim 20 \text{ eV}^2$ and the compatibility with Gallium and reactor neutrino data [19] will be discussed elsewhere [20].

the source by pion and kaon decays. The number of ν_e -induced events ($N_{\nu_e}^{\text{cal}}$) is smaller than the number of misidentified ν_μ -induced events ($N_{\nu_\mu}^{\text{cal}}$) in the low-energy bins and larger in the high-energy bins (see Fig. 1 of Ref. [1]). An increase of the total background by a factor f_ν leads to a fit of the low-energy excess through the increase of the dominant misidentified ν_μ -induced events. The high-energy bins are fitted by compensating the increase of the dominant ν_e -induced events by the factor f_ν with the disappearance of ν_e 's.

A normalization factor f_ν significantly different from unity is allowed by the 15% uncertainty of the calculated neutrino flux [23]. This uncertainty is consistent with the measured ratio 1.21 ± 0.24 of detected and predicted charged-current quasi-elastic ν_μ events [24]. Although the background calculated by the MiniBooNE collaboration has been normalized to such measured number of charged-current quasi-elastic ν_μ events, an uncertainty of about 15% remains. We consider this value as a reliable estimate of the uncertainty of the background prediction, which is more conservative than that estimated in Ref. [1].

In this paper we update the analysis presented in Ref. [6] of MiniBooNE neutrino events by considering the new data in Ref. [1] (Section 2). We discuss the compatibility of MiniBooNE neutrino data with Gallium (Section 3), reactor (Section 4) and MiniBooNE antineutrino (Section 5) data. We also consider the possibility of a violation of the CPT equality $P_{\nu_e \rightarrow \nu_e} = P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ (Section 6).

2 MiniBooNE Neutrino Data

We consider the MiniBooNE ν_e -like events from Ref. [1, 25], which are listed in Tab. 1. We fit these data with the theoretical hypothesis

$$N_{\nu,j}^{\text{the}} = f_\nu \left(P_{\nu_e \rightarrow \nu_e} N_{\nu_e,j}^{\text{cal}} + N_{\nu_\mu,j}^{\text{cal}} \right), \quad (4)$$

where $N_{\nu_e,j}^{\text{cal}}$ and $N_{\nu_\mu,j}^{\text{cal}}$ are, respectively, the calculated number of expected ν_e -induced and misidentified ν_μ -induced events in the third and fourth columns of Tab. 1. We calculate the best fit values of the parameters $P_{\nu_e \rightarrow \nu_e}$ and f_ν by minimizing the least-square function

$$\chi_{\text{MB-}\nu}^2 = \sum_{j=1}^{11} \frac{(N_{\nu,j}^{\text{the}} - N_{\nu,j}^{\text{exp}})^2}{N_{\nu,j}^{\text{the}}} + \left(\frac{f_\nu - 1}{\Delta f_\nu} \right)^2, \quad (5)$$

with [23]

$$\Delta f_\nu = 0.15, \quad (6)$$

according to the discussion in the introductory Section 1.

The results of the minimization of $\chi_{\text{MB-}\nu}^2$ are presented in Tab. 2 in the MB- ν column. One can see that the hypothesis of ν_e disappearance improves the fit with a significant decrease of $\chi_{\text{MB-}\nu}^2$ from 27.2 to 17.7. Note that in both cases we minimize the χ^2 with respect to f_ν , which is an intrinsic uncertainty in the MiniBooNE result. As shown in Fig. 1, the rather large best-fit value $f_\nu^{\text{bf}} = 1.31$, allows us to fit the low-energy excess by increasing the number of misidentified ν_μ -induced events, whereas the rather low best-fit value $P_{\nu_e \rightarrow \nu_e}^{\text{bf}} = 0.72$ maintains a good fit of the intermediate-energy and high-energy data by avoiding an increase of the ν_e -induced events through the product $f_\nu^{\text{bf}} P_{\nu_e \rightarrow \nu_e}^{\text{bf}} = 0.94$.

Figure 2 shows the allowed regions in the $P_{\nu_e \rightarrow \nu_e} - f_\nu$ plane. One can see that the uncertainties for the two parameters are correlated. The reason is that the product $f_\nu P_{\nu_e \rightarrow \nu_e}$ is constrained by the fitting of the intermediate-energy and high-energy data through the dominating ν_e -induced events.

The $\Delta\chi^2 = \chi_{\text{MB-}\nu}^2 - \chi_{\text{MB-}\nu, \text{min}}^2$ marginalized over f_ν is shown in Fig 3 as a function of $P_{\nu_e \rightarrow \nu_e}$. One can see that the MiniBooNE neutrino data indicate $P_{\nu_e \rightarrow \nu_e} < 1$ with 99.80% CL. The allowed ranges of $P_{\nu_e \rightarrow \nu_e}$ at different values of confidence level are listed in Tab. 3.

3 Gallium Radioactive Source Experiments

In this Section we discuss the results of a combined fit of the MiniBooNE neutrino data considered in the previous Section with the result in Eq. (2) for the ratio of measured and predicted ^{71}Ge production rates in the Gallium radioactive source experiments [13–18].

We consider the sum of the MiniBooNE neutrino least-square function in Eq. (5) with the Gallium least-square function

$$\chi_{\text{Ga}}^2 = \left(\frac{P_{\nu_e \rightarrow \nu_e} - R_{\text{Ga}}}{\Delta R_{\text{Ga}}} \right)^2, \quad (7)$$

where, from Eq. (2), $R_{\text{Ga}} = 0.87$ and $\Delta R_{\text{Ga}} = 0.05$. The results of the minimization of $\chi^2 = \chi_{\text{MB-}\nu}^2 + \chi_{\text{Ga}}^2$ are listed in Tab. 2 in the MB- ν +Ga column. The parameter goodness-of-fit [26] of 12.4% implies that the results of the MiniBooNE neutrino and the Gallium radioactive source experiments are compatible in the framework of the VSBL ν_e disappearance hypothesis. The best-fit values $f_\nu^{\text{bf}} = 1.24$ and $P_{\nu_e \rightarrow \nu_e}^{\text{bf}} = 0.83$, are more reasonable than those obtained from the fit of MiniBooNE neutrino data alone. The goodness of fit of 2.8% is acceptable and much better than the 0.04% obtained without ν_e disappearance. Figure 3 shows $\Delta\chi^2 = \chi^2 - \chi_{\text{min}}^2$ marginalized over f_ν as a function of $P_{\nu_e \rightarrow \nu_e}$. One can see that $P_{\nu_e \rightarrow \nu_e} = 1$ is disfavored at more than 3σ (the precise value is 99.98% CL). The allowed ranges of $P_{\nu_e \rightarrow \nu_e}$ at different values of confidence level are listed in Tab. 3.

As a caveat, we need to mention that another possible explanation of the Gallium anomaly³ is that the theoretical cross section of the Gallium detection process in Ref. [28], which has been used in deriving Eq. (2), has been overestimated [13, 18, 29]. This is possible, because the detection process $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$ can populate excited states of ^{71}Ge with transition amplitudes which have large uncertainties [30, 31]. Let us however remark that shell model calculations indicate [31] that the cross section of the Gallium detection process could be even larger than that used in deriving Eq. (2), leading to a stronger anomaly.

4 Reactor Neutrino Experiments

The indication in favor of VSBL ν_e disappearance that we have obtained from the data of the MiniBooNE neutrino experiment and the Gallium radioactive source experiments

³ The authors of Ref. [27] proposed yet another explanation.

must be confronted with the lack of any evidence of VSBL $\bar{\nu}_e$ disappearance in reactor experiments⁴, since $P_{\nu_e \rightarrow \nu_e} = P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ in the framework of local CPT-invariant Quantum Field Theory (see Ref. [21]).

Here we will consider the data of the following reactor experiments ($R^{(d)}$ denotes the ratio of measured and predicted event rates at the source-detector distance d):

Gosgen [33]:

$$R_{\text{Gosgen}}^{(37.9 \text{ m})} = 1.018 \pm 0.019 \pm 0.015 \pm 0.060, \quad (8)$$

$$R_{\text{Gosgen}}^{(45.9 \text{ m})} = 1.045 \pm 0.019 \pm 0.015 \pm 0.060, \quad (9)$$

$$R_{\text{Gosgen}}^{(64.7 \text{ m})} = 0.975 \pm 0.036 \pm 0.030 \pm 0.060, \quad (10)$$

where the first uncertainty is statistic, the second is uncorrelated systematic and the third is correlated systematic.

Bugey [32]:

$$R_{\text{Bugey}}^{(15 \text{ m})} = 0.988 \pm 0.004 \pm 0.05, \quad (11)$$

$$R_{\text{Bugey}}^{(40 \text{ m})} = 0.994 \pm 0.010 \pm 0.05, \quad (12)$$

$$R_{\text{Bugey}}^{(95 \text{ m})} = 0.915 \pm 0.132 \pm 0.05. \quad (13)$$

Chooz [34]:

$$R_{\text{Chooz}}^{(1 \text{ km})} = 1.01 \pm 0.028 \pm 0.027. \quad (14)$$

The Gosgen, Bugey and Chooz collaborations estimated, respectively, a 3.0% [33], a 2.8% [32], and a 1.9% [34] systematic uncertainty of the reactor neutrino flux. The estimate of the Chooz collaboration was based on the assumption that previous reactor experiments measured the reactor neutrino flux without any disappearance. Since we are considering the possibility of such a disappearance, we must increase the Chooz systematic uncertainty of the reactor neutrino flux to the same value as that of Gosgen and Bugey, i.e. approximately 3%, leading to

$$R_{\text{Chooz}}^{(1 \text{ km})} = 1.01 \pm 0.028 \pm 0.036. \quad (15)$$

Taking a 3% systematic uncertainty of the reactor neutrino flux correlated in all reactor neutrino experiments, we obtain the covariance matrix of reactor data

$$V_{\text{Re}} = \begin{pmatrix} 4.19 & 3.60 & 3.60 & 0.90 & 0.90 & 0.90 & 0.90 \\ 3.60 & 4.19 & 3.60 & 0.90 & 0.90 & 0.90 & 0.90 \\ 3.60 & 3.60 & 5.80 & 0.90 & 0.90 & 0.90 & 0.90 \\ 0.90 & 0.90 & 0.90 & 2.63 & 2.62 & 2.62 & 0.90 \\ 0.90 & 0.90 & 0.90 & 2.62 & 2.72 & 2.62 & 0.90 \\ 0.90 & 0.90 & 0.90 & 2.62 & 2.62 & 20.04 & 0.90 \\ 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 2.05 \end{pmatrix} \times 10^{-3}, \quad (16)$$

⁴ The compatibility of MiniBooNE neutrino data with the weak indication of $\bar{\nu}_e$ disappearance due $\Delta m^2 \simeq 2 \text{ eV}^2$ found in Ref. [19] from the analysis of the Bugey reactor neutrino data [32] will be discussed elsewhere [20].

for the vector of data

$$\vec{R}_{\text{Re}} = \left(R_{\text{Gosgen}}^{(37.9 \text{ m})}, R_{\text{Gosgen}}^{(45.9 \text{ m})}, R_{\text{Gosgen}}^{(64.7 \text{ m})}, R_{\text{Bugey}}^{(15 \text{ m})}, R_{\text{Bugey}}^{(40 \text{ m})}, R_{\text{Bugey}}^{(95 \text{ m})}, R_{\text{Chooz}}^{(1 \text{ km})} \right). \quad (17)$$

We fit the reactor neutrino data by minimizing the least-squares function

$$\chi_{\text{Re}}^2 = \left(P_{\nu_e \rightarrow \nu_e} - \vec{R}_{\text{Re}} \right)^T V_{\text{Re}}^{-1} \left(P_{\nu_e \rightarrow \nu_e} - \vec{R}_{\text{Re}} \right). \quad (18)$$

From the results presented in Tab. 2 and Fig. 3 one can see that reactor data do not show any indication of $\bar{\nu}_e$ disappearance.

However, the lower limits for $P_{\nu_e \rightarrow \nu_e}$ that one can infer from Fig. 3 (see Tab. 3) indicate that reactor data allow a small $\bar{\nu}_e$ disappearance. Therefore, we tried a combined analysis of MiniBooNE neutrino, Gallium and reactor data under the hypothesis of ν_e disappearance with $P_{\nu_e \rightarrow \nu_e} = P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$.

The results of the minimization of $\chi^2 = \chi_{\text{MB-}\nu}^2 + \chi_{\text{Ga}}^2 + \chi_{\text{Re}}^2$ are given in the corresponding column in Tab. 2. The rather low parameter goodness-of-fit, 0.4%, shows that there is tension between MiniBooNE and Gallium neutrino data on one side and reactor antineutrino data on the other side. The tension is mainly due to a conflict between MiniBooNE and reactor data, which have a 0.3% parameter goodness-of-fit ($\Delta\chi_{\text{min}}^2 = 8.6$ with NDF = 1), whereas Gallium and reactor data have a 3.1% parameter goodness-of-fit ($\Delta\chi_{\text{min}}^2 = 4.6$ with NDF = 1).

Possible explanations of this tension could be:

1. Statistical fluctuations.
2. Systematic uncertainties have been underestimated.
3. Our hypothesis of VSBL ν_e disappearance is excluded.
4. There is a violation of CPT symmetry leading to $P_{\nu_e \rightarrow \nu_e} \neq P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$.

Considering the first possibility, the combined fit of MiniBooNE neutrino, Gallium and reactor data leads to the $\Delta\chi^2 = \chi^2 - \chi_{\text{min}}^2$ depicted in Fig. 3 and the allowed ranges of $P_{\nu_e \rightarrow \nu_e}$ listed in Tab. 3. One can see that the addition of the reactor constraint narrows the allowed range of $P_{\nu_e \rightarrow \nu_e}$ and shifts it towards unity. There is an indication that $P_{\nu_e \rightarrow \nu_e} < 1$ with 97.74% CL.

Figure 4 shows that the fit of the MiniBooNE neutrino data with the best-fit values $f_{\nu}^{\text{bf}} = 1.19$ and $P_{\nu_e \rightarrow \nu_e}^{\text{bf}} = 0.93$ is not as good as that in Fig. 1 corresponding to the fit of MiniBooNE neutrino data alone, but it is acceptable. We notice that the value of f_{ν}^{bf} is not much different from that obtained from the fit of MiniBooNE neutrino data without oscillations ($f_{\nu}^{\text{bf}} = 1.15$; see Tab. 2). It is only slightly larger, in order to keep the product $f_{\nu}^{\text{bf}} P_{\nu_e \rightarrow \nu_e}^{\text{bf}} = 1.11$ close to unity for a good fit of the intermediate-energy and high-energy MiniBooNE neutrino data.

5 MiniBooNE Antineutrino Data

The MiniBooNE collaboration presented recently the first results on the search for $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$ oscillations [4, 5]. These data, as the neutrino data, do not show any evidence for

a signal in the 475 – 3000 MeV energy range due to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations compatible with the indication found in the LSND experiment. There is also no evidence of a low-energy anomalous excess of events analogous to that observed in the neutrino data. However, since in MiniBooNE the antineutrino statistics is about five times smaller than the neutrino statistics, the uncertainties of the antineutrino data do not allow us to infer strong constraints on new physics.

In this section we study the compatibility of the VSBL ν_e disappearance hypothesis with the MiniBooNE antineutrino data, assuming the CPT equality $P_{\nu_e \rightarrow \nu_e} = P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$. We fit the MiniBooNE antineutrino data with the theoretical hypothesis

$$N_{\bar{\nu},j}^{\text{the}} = f_{\bar{\nu}} \left(P_{\nu_e \rightarrow \nu_e} N_{\bar{\nu}_e,j}^{\text{cal}} + N_{\bar{\nu}_\mu,j}^{\text{cal}} \right), \quad (19)$$

where $N_{\bar{\nu}_e,j}^{\text{cal}}$ and $N_{\bar{\nu}_\mu,j}^{\text{cal}}$ are, respectively, the calculated number of expected $\bar{\nu}_e$ -induced and misidentified $\bar{\nu}_\mu$ -induced events in the third and fourth columns of Tab. 4. The least-squares function is

$$\chi_{\text{MB-}\bar{\nu}}^2 = \sum_{j=1}^{11} \frac{(N_{\bar{\nu},j}^{\text{the}} - N_{\bar{\nu},j}^{\text{exp}})^2}{N_{\bar{\nu},j}^{\text{the}}} + \left(\frac{f_{\bar{\nu}} - 1}{\Delta f_{\bar{\nu}}} \right)^2, \quad (20)$$

with [23]

$$\Delta f_{\bar{\nu}} = 0.17. \quad (21)$$

The minimum of $\chi_{\text{MB-}\bar{\nu}}^2$ is obtained for $P_{\nu_e \rightarrow \nu_e} = 1$, as shown in Tab. 5. However, the low statistics of the data do not allow us to put stringent constraints on $P_{\nu_e \rightarrow \nu_e}$, as one can see from the $\Delta\chi^2 = \chi_{\text{MB-}\bar{\nu}}^2 - \chi_{\text{MB-}\bar{\nu},\text{min}}^2$ marginalized over $f_{\bar{\nu}}$ depicted in Fig. 3 (MB- $\bar{\nu}$ curve) and the allowed ranges of $P_{\nu_e \rightarrow \nu_e}$ listed in Tab. 3.

In fact, the parameter goodness-of-fit of 14.8% of the combined fit of MiniBooNE neutrino and antineutrino data is acceptable. The $\Delta\chi^2 = \chi^2 - \chi_{\text{min}}^2$, where $\chi^2 = \chi_{\text{MB-}\nu}^2 + \chi_{\text{MB-}\bar{\nu}}^2$, depicted in Fig. 3 (MB curve) shows that the MiniBooNE neutrino data are dominating.

Finally, in Tab. 5 and Fig. 3 we present the results of the combined fit MB+Ga+Re of all the data considered so far: the MiniBooNE neutrino and antineutrino data and the Gallium and reactor data. The parameter goodness-of-fit of 4.1% do not allow us to reject the compatibility of the data under the hypothesis of VSBL ν_e disappearance. This results indicate that the possibility that the tension between MiniBooNE neutrino and Gallium data on one side and reactor data on the other side is due to statistical fluctuations may be correct. In this case, from Fig. 3 one can see that $P_{\nu_e \rightarrow \nu_e} < 1$ with 97.04% CL. Therefore, adding the MiniBooNE antineutrino data to the combined fit of MiniBooNE, Gallium and reactor data does not change significantly the confidence level of the indication of $P_{\nu_e \rightarrow \nu_e} < 1$ found in Section 4. Indeed, the best fit values of $P_{\nu_e \rightarrow \nu_e}$ and f_ν (see Tabs. 2 and 5) and the allowed ranges of $P_{\nu_e \rightarrow \nu_e}$ listed in Tab. 3 are practically the same as those obtained without the MiniBooNE antineutrino data. Therefore, Fig. 4 and the related discussion at the end of Section 4 remain valid after the addition of MiniBooNE antineutrino data.

6 CPT Violation

In this section we consider a violation [35–43] of the CPT equality $P_{\nu_e \rightarrow \nu_e} = P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ as a possible explanation of the tension between MiniBooNE and Gallium neutrino data on one side and reactor antineutrino data on the other side under the hypothesis of ν_e disappearance. We quantify the amount of CPT violation through the asymmetry

$$A_{ee}^{\text{CPT}} \equiv P_{\nu_e \rightarrow \nu_e} - P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}. \quad (22)$$

Taking into account for completeness also the MiniBooNE neutrino data, we minimized the least-squares function $\chi^2 = \chi_{\text{MB-}\nu}^2 + \chi_{\text{Ga}}^2 + \chi_{\text{Re}}^2 + \chi_{\text{MB-}\bar{\nu}}^2$, with $P_{\nu_e \rightarrow \nu_e}$ replaced by $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ in Eqs. (18) and (19). We obtained, for 26 degrees of freedom,

$$\chi_{\text{min}}^2 = 39.9, \quad \text{GoF} = 4.0\%, \quad A_{ee}^{\text{CPT,bf}} = -0.17. \quad (23)$$

The relatively low goodness of fit is due to the relatively low goodness of fit of the MiniBooNE neutrino and antineutrino data (see Tabs. 2 and 5). Figure 5 shows the marginal $\Delta\chi^2 = \chi^2 - \chi_{\text{min}}^2$ as a function of A_{ee}^{CPT} . One can see that there is indication of CPT violation ($A_{ee}^{\text{CPT}} < 0$) at 99.7% CL. The allowed intervals for A_{ee}^{CPT} at 90%, 95.45%, 99%, and 99.73% CL are, respectively,

$$A_{ee}^{\text{CPT}} = [-0.24, -0.08], [-0.25, -0.06], [-0.28, -0.02], [-0.30, 0.00]. \quad (24)$$

Let us emphasize that the possibility of CPT violation is extremely interesting and should be explored in future experiments by measuring the CPT asymmetries (see Ref. [21])

$$A_{\alpha\beta}^{\text{CPT}} \equiv P_{\nu_\alpha \rightarrow \nu_\beta} - P_{\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha}, \quad (25)$$

with $\alpha, \beta = e, \mu$. The realization of a CPT violation would have dramatic consequences for our understanding of fundamental physics [44, 45]. Since the indication of CPT violation that we have found has been obtained under the hypothesis of ν_e disappearance into sterile neutrinos, it could be due to very exotic CPT-violating properties of the sterile neutrinos.

7 Conclusions

We have shown that the MiniBooNE low-energy neutrino anomaly [1, 2] can be explained by a VSBL ν_e disappearance [6] which is compatible with that inferred from the Gallium radioactive source experiment anomaly [6, 11–18]. There is a tension between this result and the absence of any indication of $\bar{\nu}_e$ disappearance in reactor neutrino data [32–34] which could be due to statistical fluctuations, or to an underestimation of systematic uncertainties, or to the inexistence of VSBL ν_e disappearance, or to a violation of the CPT equality $P_{\nu_e \rightarrow \nu_e} = P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$. Considering the first possibility, we have shown that the combined fit of MiniBooNE neutrino, Gallium and reactor data indicate that $P_{\nu_e \rightarrow \nu_e} < 1$ at about 2σ .

We have considered the first MiniBooNE results on $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations [4, 5]. Since the MiniBooNE antineutrino statistics is about five times smaller than the neutrino statistics, the antineutrino data do not allow us to infer strong constraints on the VSBL ν_e

disappearance hypothesis. We have shown that MiniBooNE antineutrino data are compatible with the MiniBooNE neutrino data and that adding the MiniBooNE antineutrino data to the combined fit of MiniBooNE, Gallium and reactor data does not change the indication of $P_{\nu_e \rightarrow \nu_e} < 1$ at about 2σ .

We think that the possible VSBL ν_e disappearance discussed in this paper is extremely interesting, because such disappearance is due to a Δm^2 which is much larger than the well measured solar and atmospheric Δm^2 's (see Ref. [46]). Hence, our result indicate the possible existence of a light sterile neutrino which is well beyond the Standard Model and would have important consequences in physics (see Refs. [47–54]), astrophysics (see Refs. [55–60]), and cosmology (see Refs. [61–63]).

We have considered also the possibility of CPT violation as the source of the tension between the neutrino and antineutrino data. For the asymmetry of the ν_e and $\bar{\nu}_e$ survival probabilities we have obtained the best-fit value $A_{ee}^{\text{CPT,bf}} = -0.17$ and the constraint $A_{ee}^{\text{CPT}} < 0$ at 99.7% CL. Since the violation of CPT would have dramatic consequences for our understanding of fundamental physics, we think that it should be investigated without prejudice in future experiments. It could be due to very exotic CPT-violating properties of the sterile neutrinos into which ν_e disappear in our hypothesis for the explanation of the MiniBooNE and Gallium anomalies.

Starting from 2010, at the same L/E of MiniBooNE, the magnetic near detector at 280 m of the T2K experiment at Tokai [64] will count ν_e events with expected higher statistics and similar ν_μ background contamination. A better ν_μ background rejection will be possible using the liquid Argon technology, as planned in the the MicroBooNE proposal at Fermilab [65], that will check the low-energy MiniBooNE anomaly.

The hypothesis of VSBL ν_e disappearance can be tested with high accuracy by future experiments with pure electron neutrino beams. The SAGE collaboration is planning to perform a new source experiment [13] in order to check the Gallium anomaly in Eq. (2). A similar measurement could be made in the LENS detector [66]. Beta-beam experiments [67,68] with pure ν_e or $\bar{\nu}_e$ beams from nuclear decay (see the reviews in Refs. [69,70]) could investigate the disappearance of electron neutrinos and antineutrinos, testing the CPT symmetry. The same can be done, with higher precision, in neutrino factory experiments in which the beam is composed of ν_e and $\bar{\nu}_\mu$, from μ^+ decay, or $\bar{\nu}_e$ and ν_μ , from μ^- decay (see the reviews in Refs. [69,71]). A Mossbauer neutrino experiment [72], with a $\bar{\nu}_e$ beam produced in recoilless ^3H decay and detected in recoilless ^3He antineutrino capture, would be especially suited to investigate the VSBL disappearance of electron antineutrinos.

Acknowledgments

We would like to thank William C. Louis III for information about MiniBooNE neutrino data and Carlo Bemporad and Donato Nicoló for information about the Chooz experiment. We are grateful to Milla Baldo Ceolin for discussions and suggestions. C. Giunti would like to thank the Department of Theoretical Physics of the University of Torino for hospitality and support.

References

- [1] MiniBooNE, A.A. Aguilar-Arevalo, Phys. Rev. Lett. 102 (2009) 101802, [arXiv:0812.2243](#).
- [2] MiniBooNE, A. Aguilar-Arevalo et al., Phys. Rev. Lett. 98 (2007) 231801, [arXiv:0704.1500](#).
- [3] LSND, A. Aguilar et al., Phys. Rev. D64 (2001) 112007, [arXiv:hep-ex/0104049](#).
- [4] MiniBooNE, G. Karagiorgi, (2008), FNAL Seminar, 11 December 2008. URL: <http://theory.fnal.gov/jetp/talks/karagiorgi.pdf>.
- [5] MiniBooNE, A.A. Aguilar-Arevalo et al., (2009), [arXiv:0904.1958](#).
- [6] C. Giunti and M. Laveder, Phys. Rev. D77 (2008) 093002, [arXiv:0707.4593](#).
- [7] J.A. Harvey, C.T. Hill and R.J. Hill, Phys. Rev. Lett. 99 (2007) 261601, [arXiv:0708.1281](#).
- [8] J.A. Harvey, C.T. Hill and R.J. Hill, Phys. Rev. D77 (2008) 085017, [arXiv:0712.1230](#).
- [9] A. Bodek, (2007), [arXiv:0709.4004](#).
- [10] A.E. Nelson and J. Walsh, Phys. Rev. D77 (2008) 033001, [arXiv:0711.1363](#).
- [11] M. Laveder, Nucl. Phys. Proc. Suppl. 168 (2007) 344, NOW 2006.
- [12] C. Giunti and M. Laveder, Mod. Phys. Lett. A22 (2007) 2499, [arXiv:hep-ph/0610352](#).
- [13] SAGE, J.N. Abdurashitov et al., (2009), [arXiv:0901.2200](#).
- [14] GALLEX, P. Anselmann et al., Phys. Lett. B342 (1995) 440.
- [15] GALLEX, W. Hampel et al., Phys. Lett. B420 (1998) 114.
- [16] SAGE, J.N. Abdurashitov et al., Phys. Rev. Lett. 77 (1996) 4708.
- [17] SAGE, J.N. Abdurashitov et al., Phys. Rev. C59 (1999) 2246, [arXiv:hep-ph/9803418](#).
- [18] J.N. Abdurashitov et al., Phys. Rev. C73 (2006) 045805, [arXiv:nucl-ex/0512041](#).
- [19] M.A. Acero, C. Giunti and M. Laveder, Phys. Rev. D78 (2008) 073009, [arXiv:0711.4222](#).
- [20] C. Giunti and M. Laveder, (2009), In preparation.
- [21] C. Giunti and C.W. Kim, Fundamentals of Neutrino Physics and Astrophysics (Oxford University Press, 2007).

- [22] S.E. Kopp, Phys. Rept. 439 (2007) 101, [arXiv:physics/0609129](#), NuFact Summer School.
- [23] MiniBooNE, A.A. Aguilar-Arevalo et al., (2008), [arXiv:0806.1449](#).
- [24] MiniBooNE, A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. 100 (2008) 032301, [arXiv:0706.0926](#).
- [25] W.C. Louis, (2009), Private communication.
- [26] M. Maltoni and T. Schwetz, Phys. Rev. D68 (2003) 033020, [arXiv:hep-ph/0304176](#).
- [27] Y. Farzan, T. Schwetz and A.Y. Smirnov, JHEP 07 (2008) 067, [arXiv:0805.2098](#).
- [28] J.N. Bahcall, Phys. Rev. C56 (1997) 3391, [arXiv:hep-ph/9710491](#).
- [29] G. Fogli et al., (2006), [arXiv:hep-ph/0605186](#), 3rd International Workshop on NO-VE: Neutrino Oscillations in Venice: 50 Years after the Neutrino Experimental Discovery, Venice, Italy, 7–10 Feb 2006.
- [30] N. Hata and W. Haxton, Phys. Lett. B353 (1995) 422, [arXiv:nucl-th/9503017](#).
- [31] W.C. Haxton, Phys. Lett. B431 (1998) 110, [arXiv:nucl-th/9804011](#).
- [32] Bugey, B. Achkar et al., Nucl. Phys. B434 (1995) 503.
- [33] CalTech-SIN-TUM, G. Zacek et al., Phys. Rev. D34 (1986) 2621.
- [34] CHOOZ, M. Apollonio et al., Eur. Phys. J. C27 (2003) 331, [arXiv:hep-ex/0301017](#).
- [35] V.A. Kostelecky and R. Lehnert, Phys. Rev. D63 (2001) 065008, [arXiv:hep-th/0012060](#).
- [36] G. Barenboim et al., JHEP 10 (2002) 001, [arXiv:hep-ph/0108199](#).
- [37] A. De Gouvea, Phys. Rev. D66 (2002) 076005, [arXiv:hep-ph/0204077](#).
- [38] A. Kostelecky and M. Mewes, Phys. Rev. D70 (2004) 031902, [arXiv:hep-ph/0308300](#).
- [39] V.A. Kostelecky and M. Mewes, Phys. Rev. D69 (2004) 016005, [arXiv:hep-ph/0309025](#).
- [40] F.R. Klinkhamer and G.E. Volovik, Int. J. Mod. Phys. A20 (2005) 2795, [arXiv:hep-th/0403037](#).
- [41] F. Klinkhamer, JETP Lett. 79 (2004) 451, [arXiv:hep-ph/0403285](#).
- [42] T. Katori, V.A. Kostelecky and R. Tayloe, Phys. Rev. D74 (2006) 105009, [arXiv:hep-ph/0606154](#).

- [43] P. Arias et al., Phys. Lett. B650 (2007) 401, [arXiv:hep-ph/0608007](#).
- [44] G. Barenboim et al., Phys. Lett. B537 (2002) 227, [arXiv:hep-ph/0203261](#).
- [45] O. Greenberg, Found. Phys. 36 (2006) 1535, [arXiv:hep-ph/0309309](#).
- [46] M. Maltoni and T. Schwetz, (2008), [arXiv:0812.3161](#), IDM2008, Aug. 18-22, 2008, Stockholm, Sweden.
- [47] G. Karagiorgi et al., Phys. Rev. D75 (2007) 013011, [arXiv:hep-ph/0609177](#).
- [48] C. Grieb, J. Link and R.S. Raghavan, In Phys. Rev. [66], p. 093006, [arXiv:hep-ph/0611178](#).
- [49] D.C. Latimer, J. Escamilla and D.J. Ernst, Phys. Rev. C75 (2007) 042501, [arXiv:hep-ex/0701004](#).
- [50] A. Donini et al., JHEP 12 (2007) 013, [arXiv:0704.0388](#).
- [51] M. Maltoni and T. Schwetz, Phys. Rev. D76 (2007) 093005, [arXiv:0705.0107](#).
- [52] S. Goswami and W. Rodejohann, JHEP 10 (2007) 073, [arXiv:0706.1462](#).
- [53] A. Bandyopadhyay and S. Choubey, (2007), [arXiv:0707.2481](#).
- [54] T. Schwetz, JHEP 02 (2007) 011, [arXiv:0710.2985](#).
- [55] R.L. Awasthi and S. Choubey, Phys. Rev. D76 (2007) 113002, [arXiv:0706.0399](#).
- [56] S. Choubey, JHEP 12 (2007) 014, [arXiv:0709.1937](#).
- [57] D. Boyanovsky, H.J. de Vega and N. Sanchez, Phys. Rev. D77 (2008) 043518, [arXiv:0710.5180](#).
- [58] G. Gentile, H.S. Zhao and B. Famaey, (2007), [arXiv:0712.1816](#).
- [59] G.W. Angus, (2008), [arXiv:0805.4014](#).
- [60] A. Donini and O. Yasuda, (2008), [arXiv:0806.3029](#).
- [61] O. Civitarese and M.E. Mosquera, Phys. Rev. C77 (2008) 045806, [arXiv:0711.2450](#).
- [62] A. Melchiorri et al., JCAP 0901 (2008) 036, [arXiv:0810.5133](#).
- [63] M.A. Acero and J. Lesgourgues, Phys. Rev. D79 (2009) 045026, [arXiv:0812.2249](#).
- [64] T2K, T. Lindner et al., (2008), [arXiv:0810.2220](#), ICHEP08.
- [65] MicroBooNE, H. Chen et al., (2008), URL: http://www-microboone.fnal.gov/Documents/MicroBooNE_addendum/MicroBooNEAddendum_030308.pdf
- [66] C. Grieb, J. Link and R.S. Raghavan, Phys. Rev. D75 (2007) 093006, [arXiv:hep-ph/0611178](#).

- [67] P. Zucchelli, Phys. Lett. B532 (2002) 166.
- [68] C. Rubbia et al., Nucl. Instrum. Meth. A568 (2006) 475, [arXiv:hep-ph/0602032](#).
- [69] Neutrino Factory/Muon Collider, C. Albright et al., (2004), [arXiv:physics/0411123](#).
- [70] C. Volpe, J. Phys. G34 (2007) R1, [arXiv:hep-ph/0605033](#).
- [71] M. Apollonio et al., (2002), [arXiv:hep-ph/0210192](#).
- [72] R.S. Raghavan, (2006), [arXiv:hep-ph/0601079](#).

j	Energy Range [MeV]	$N_{\nu_e,j}^{\text{cal}}$	$N_{\nu_\mu,j}^{\text{cal}}$	$N_{\nu_j,j}^{\text{cal}}$	$N_{\nu_j,j}^{\text{exp}}$
1	200 – 300	18.8	168.0	186.8	232
2	300 – 375	23.4	85.0	108.4	156
3	375 – 475	40.6	79.8	120.4	156
4	475 – 550	31.6	32.7	64.3	79
5	550 – 675	50.8	39.7	90.5	81
6	675 – 800	49.9	17.9	67.8	70
7	800 – 950	52.7	17.8	70.5	63
8	950 – 1100	44.3	13.3	57.6	65
9	1100 – 1300	42.5	9.9	52.4	62
10	1300 – 1500	33.8	5.3	39.1	34
11	1500 – 3000	56.7	15.5	72.2	71

Table 1: MiniBooNE neutrino data [1, 25]. The six columns give: 1) bin number; 2) reconstructed neutrino energy range; 3) number of expected ν_e -induced events; 4) number of expected misidentified ν_μ -induced events; 5) total number of expected events; 6) measured number of events.

		MB- ν	MB- ν +Ga	Re	MB- ν +Ga+Re
No Osc.	χ_{\min}^2	27.2	34.0	2.9	36.9
	NDF	10	11	7	18
	GoF	0.2%	0.04%	89.8%	0.5%
	f_{ν}^{bf}	1.15	1.15		1.15
Osc.	χ_{\min}^2	17.7	20.1	2.9	31.7
	NDF	9	10	6	17
	GoF	3.8%	2.8%	82.7%	1.7%
	$P_{\nu_e \rightarrow \nu_e}^{\text{bf}}$	0.72	0.83	1.0	0.93
	f_{ν}^{bf}	1.31	1.24		1.19
PG	$\Delta\chi_{\min}^2$		2.4		11.1
	NDF		1		2
	GoF		12.4%		0.4%

Table 2: Values of χ^2 , number of degrees of freedom (NDF) and goodness-of-fit (GoF) for the fit of different combinations of MiniBooNE neutrino (MB- ν), Gallium (Ga) and reactor (Re) data. The first four lines correspond to the case of no oscillations (No Osc.). The following five lines correspond to the case of oscillations (Osc.). The last three lines give the parameter goodness-of-fit (PG) [26].

	BF	68.27%	90%	95.45%	99%	99.73%
MB- ν	0.72	0.65 - 0.80	0.60 - 0.86	0.58 - 0.89	0.54 - 0.95	0.52 - 0.99
MB- ν +Ga	0.83	0.79 - 0.88	0.76 - 0.91	0.75 - 0.92	0.72 - 0.95	0.70 - 0.97
Re	1.00	0.97 - 1.00	0.94 - 1.00	0.93 - 1.00	0.91 - 1.00	0.89 - 1.00
MB- ν +Ga+Re	0.93	0.90 - 0.96	0.89 - 0.98	0.88 - 0.99	0.86 - 1.00	0.85 - 1.00
MB- $\bar{\nu}$	1.00	0.83 - 1.00	0.70 - 1.00	0.63 - 1.00	0.54 - 1.00	0.47 - 1.00
MB- $\bar{\nu}$ +Re	1.00	0.97 - 1.00	0.95 - 1.00	0.93 - 1.00	0.91 - 1.00	0.89 - 1.00
MB	0.76	0.69 - 0.84	0.65 - 0.90	0.62 - 0.93	0.59 - 0.98	0.56 - 1.00
MB+Ga+Re	0.93	0.91 - 0.96	0.89 - 0.98	0.88 - 0.99	0.86 - 1.00	0.85 - 1.00

Table 3: Best-fit values (BF) and allowed ranges of $P_{\nu_e \rightarrow \nu_e}$ at the indicated value of confidence level for the fits in Tabs. 2 and 5.

j	Energy Range [MeV]	$N_{\bar{\nu}_e, j}^{\text{cal}}$	$N_{\bar{\nu}_\mu, j}^{\text{cal}}$	$N_{\bar{\nu}, j}^{\text{cal}}$	$N_{\bar{\nu}, j}^{\text{exp}}$
1	200 – 300	4.3	22.5	26.8	24
2	300 – 375	4.2	11.4	15.6	21
3	375 – 475	7.0	11.1	18.1	16
4	475 – 550	5.4	4.7	10.1	14
5	550 – 675	6.9	5.0	11.8	22
6	675 – 800	7.4	3.0	10.3	9
7	800 – 950	7.7	3.0	10.7	5
8	950 – 1100	6.3	2.7	9.0	7
9	1100 – 1300	5.8	2.3	8.1	5
10	1300 – 1500	4.2	1.6	5.8	7
11	1500 – 3000	9.5	2.5	12.0	14

Table 4: MiniBooNE antineutrino data extracted from the figure in page 55 of Ref. [4]. The six columns give: 1) bin number; 2) reconstructed antineutrino energy range; 3) number of expected $\bar{\nu}_e$ -induced events; 4) number of expected misidentified $\bar{\nu}_\mu$ -induced events; 5) total number of expected events; 6) measured number of events.

		MB- $\bar{\nu}$	MB- $\bar{\nu}$ +Re	MB	MB+Ga+Re
No Osc.	χ^2_{\min}	16.9	19.8	44.1	53.8
	NDF	10	17	21	29
	GoF	7.6%	28.5%	0.2%	0.3%
	$f_{\bar{\nu}}^{\text{bf}}$	1.08	1.08	1.08	1.08
Osc.	χ^2_{\min}	16.9	19.8	36.7	48.9
	NDF	9	16	19	27
	GoF	5.0%	23.0%	0.9%	0.6%
	$P_{\nu_e \rightarrow \nu_e}^{\text{bf}}$	1.00	1.00	0.76	0.93
	$f_{\bar{\nu}}^{\text{bf}}$	1.08	1.08	1.19	1.10
	f_{ν}^{bf}			1.28	1.19
PG	$\Delta\chi^2_{\min}$		0.0	2.1	8.3
	NDF		1	1	3
	GoF		100.0%	14.8%	4.1%

Table 5: Values of χ^2 , number of degrees of freedom (NDF) and goodness-of-fit (GoF) for the fit of MiniBooNE antineutrino (MB- $\bar{\nu}$), MiniBooNE antineutrino and reactor (MB- $\bar{\nu}$ +Re), MiniBooNE neutrino and antineutrino (MB) and MiniBooNE neutrino and antineutrino, Gallium and reactor (MB+Ga+Re) data. The first four lines correspond to the case of no oscillations (No Osc.). The following six lines correspond to the case of oscillations (Osc.). The last three lines give the parameter goodness-of-fit (PG) [26].

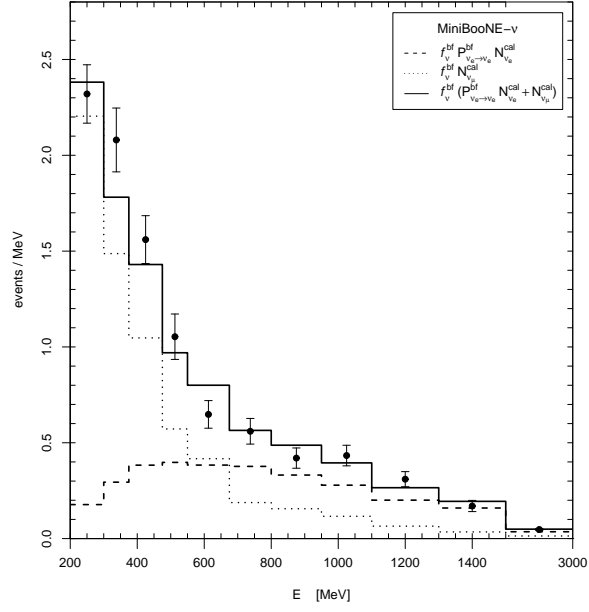


Figure 1: Theoretically expected number of ν_e events compared with MiniBooNE data, represented by the points with their statistical error bars. The values of f_ν^{bf} and $P_{\nu_e \rightarrow \nu_e}^{\text{bf}}$ are those in Tab. 2, corresponding to the best fit of MiniBooNE neutrino data (MB- ν).

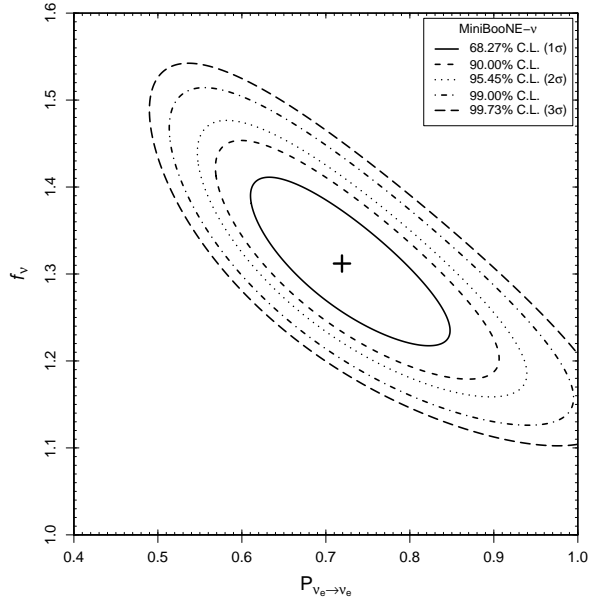


Figure 2: Allowed regions in the $P_{\nu_e \rightarrow \nu_e} - f_\nu$ plane obtained from the fit of MiniBooNE neutrino data.

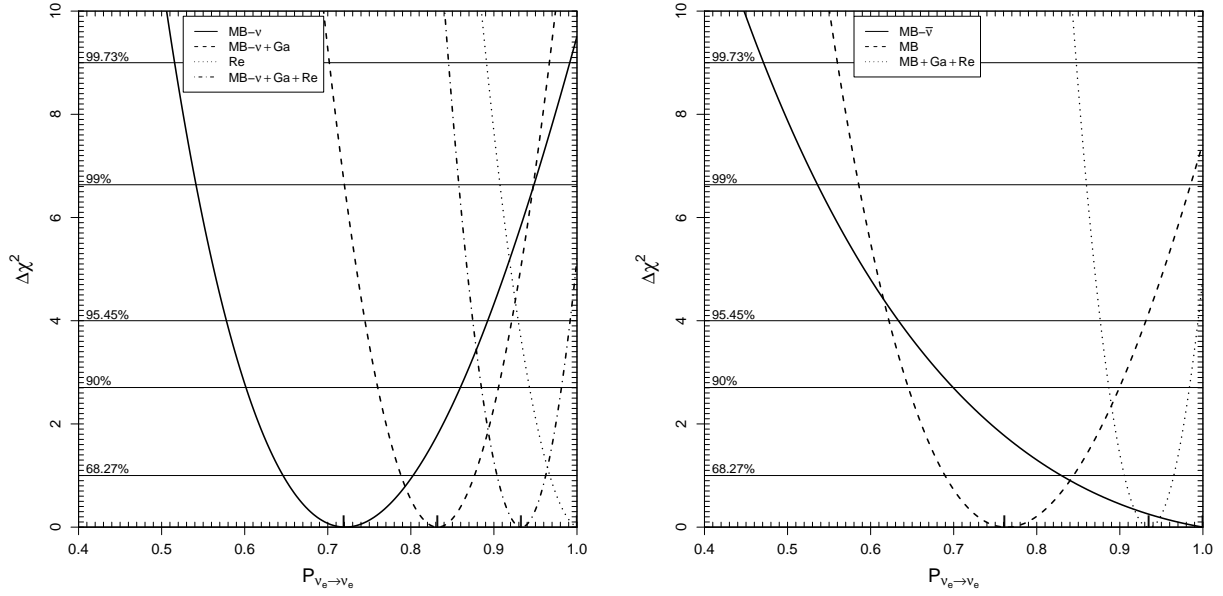


Figure 3: Marginal $\Delta\chi^2$'s as a function of $P_{\nu_e \rightarrow \nu_e}$ obtained from the fit of different combinations of MiniBooNE neutrino (MB- ν) and antineutrino (MB- $\bar{\nu}$), Gallium (Ga) and reactor (Re) data. The horizontal lines correspond to the indicated value of confidence level.

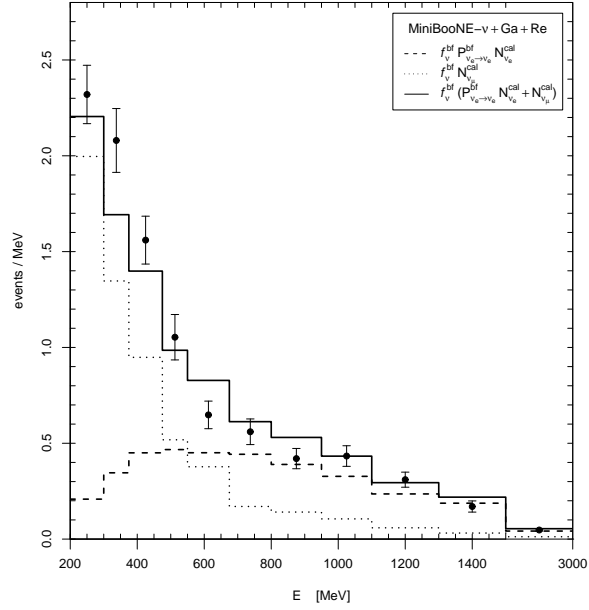


Figure 4: Theoretically expected number of ν_e events compared with MiniBooNE data, represented by the points with their statistical error bars. The values of f_{ν}^{bf} and $P_{\nu_e \rightarrow \nu_e}^{\text{bf}}$ are those in Tab. 2, corresponding to the best fit of MiniBooNE neutrino data, Gallium data and reactor data (MB- ν +Ga+Re).

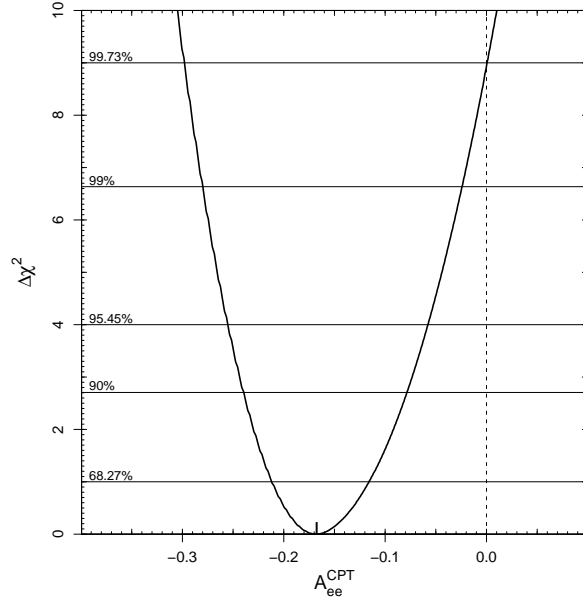


Figure 5: Marginal $\Delta\chi^2$ as a function of the CPT asymmetry A_{ee}^{CPT} in Eq. (22) obtained from the fit of MiniBooNE, Gallium and reactor data.